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Evaluating metaphor reification in tangible interfaces

Augusto Celentano[1] · Emmanuel Dubois[2]

Abstract Metaphors are a powerful conceptual device to reason about human actions. As such, they have been heavily used in designing and describing human computer interaction. Since they can address scripted text, verbal expression, imaging, sound, and gestures, they can also be considered in the design and analysis of multimodal interfaces. In this paper we discuss the description and evaluation of the relations between metaphors and their implementation in human computer interaction with a focus on tangible user interfaces (TUIs), a form of multimodal interface. The objective of this paper is to define how metaphors appear in a tangible context in order to support their evaluation. Relying on matching entities and operations between the domain of interaction and the domain of the digital application, we propose a conceptual framework based on three components: a structured representation of the mappings holding between the metaphor source, the metaphor target, the interface and the digital system; a conceptual model for describing metaphorical TUIs; three relevant properties, coherence, coverage and compliance, which define at what extent the implementation of a metaphorical tangible interface matches the metaphor. The conceptual framework is then validated and applied on a tangible prototype in an educational application.

Keywords Human computer interaction · Metaphor · Multimodality · Tangible interface

✉ Emmanuel Dubois
emmanuel.dubois@irit.fr

Augusto Celentano
auce@dais.unive.it

[1] DAIS, Università Ca' Foscari Venezia, Venice, Italy

[2] IRIT, Université Paul Sabatier, CNRS, Toulouse, France

1 Introduction

A *metaphor* is a figure of speech consisting in the expression of a concept of a *target* domain using another concept in a different domain, called *source* domain, more familiar in some context of discourse [14,49]. It is therefore a mapping between two conceptual domains. An *interaction metaphor* is a mapping between the conceptual domain that describes the interaction, which is the metaphor source, and the application domain in which a digital system is operated, which is the metaphor target. The mapping relates concepts and operations between the two domains so that an interaction in the metaphor source domain corresponds, in the target domain, to the execution of the application and the reception of computation results. Metaphors are thus means to understand how an interface works based on a known domain, and help users to learn concepts, operations and tasks of a digital application by similitude or reference to concepts, operations and tasks in a more familiar domain [10,11].

Metaphors are common in HCI since the development of GUIs, the most notable example being the *desktop metaphor*, introduced by Alan Kay in 1970s [44], which assimilates the computer monitor to a desk with documents, files and tools mimicking usual office operations: for example, a document icon dragged over the basket causes the document deletion, while a document icon dragged from one folder to another causes the document to be moved from one directory to another. GUI metaphors, and interface metaphors in general, have been discussed extensively in the literature [6,7,9,29,55].

Partial and inconsistent metaphors (like the so-called *mixed metaphors*) have also been analyzed; they are widely accepted in GUIs because they are in use long since and have become a standard pattern of operations: for example, in early Apple Macintosh GUI a disk icon dragged over a basket caused the disk to be ejected, not erased, and a document icon dragged from one folder to a different storage device resulted in copying rather than moving the file, without noticeable differences in the visual representation of the operation. Visual cues have been added in more recent systems to distinguish such different behaviors: the basket icon turns into an eject symbol for disks, while during copy the file icon is marked by a small '+' sign. This is a first example of how metaphors relate to multimodality, since the actual action is made evident by a visual feedback added to the gesture.

The development of multimodal interaction is resulting from the evolution of HCI model. Quoting Price and Jewitt [65, p. 44] "multimodal approaches provide concepts, methods and a framework for the collection and analysis of visual, aural, embodied, and spatial aspects of interaction and environments, and the relationships between these". The latter aspects (spatial aspects and environments) have been even more significant with the raise of new forms of communications, new technologies and growing capabilities of computer systems: advanced forms of HCI have been developed, including mixed and augmented reality, ubiquitous systems and tangible interfaces. Their primary goal is to combine the physical and digital worlds to better support the user's interaction with a system. Concretely, they promote and adopt a smooth integration of physical artifacts, aptitudes and habits into the manipulation and perception of digital concepts and features.

More formally, such interactive systems are implicitly making use of different forms of feedback: kinesthetic feedback results from the grasping of physical object; visual feedback is required to localize the physical artifact used in addition to the visual feedback that may be provided by the application itself; gestures are required to physically act on elements of the environment. They are thus well representing one advanced form of multimodal interaction. More precisely, according to the complementarity, assignment, redundancy, equivalence properties (CARE) defined to characterize the combination of use of different modes in multimodal interfaces [19], focusing on the user's manipulation of a TUI, a complementary use of different modalities is required to locate the artifacts, manipulate them and feel them. Multiple TUIs can of course be combined to offer also assignment, redundancy and equivalence properties.

The advent of tangible user interfaces (TUIs) has made metaphors even more popular but also difficult to evaluate, due to the presence of an additional layer represented by the physical interface which, in many cases, mediate through a metaphor the functions assigned to interface objects. Advanced interfaces based on gesture interaction in pervasive environments share with TUIs a mixture of real and virtual components, where metaphors can support users shortening the interaction learning process.

The variety of metaphor types and their increasing use in interactive digital applications has raised the issues of evaluating them. Evaluation might concern several facets: the way a metaphor is conceived or selected, to assess if it is suitable for the digital application; the degree of correspondence between the concepts of the source domain and the implementation of the digital application interface; the ease of use, naturalness, appropriateness, consistency, goodness; the affordance of the interaction devices, and so on. Evaluation often relies on an intuitive understanding of such properties in the context of human experience, but formal and structured approaches have been proposed [1,2]. Indeed, a good metaphor doesn't imply an efficient interface, and viceversa, but a good metaphor can help a user while a bad metaphor could mislead him/her [59].

In this paper we discuss the description and the evaluation of interaction metaphors with a focus on mixed reality and more specifically on tangible interfaces. Our analysis does not refer to the way a metaphor is designed or created; rather, the goal of our work is to allow designers to evaluate at what extent a tangible interface is a *reification* of the metaphor [15], i.e., (1) how the elements of the interface reflect the concepts of the source metaphor domain and (2) at what extent the implementation of a (metaphorical) interface matches the metaphor: assuming the metaphor is well chosen, is it implemented consistently? Does it cover the span of the source domain in terms of concepts, interaction objects, functions, actions, etc? Are the interface objects (i.e., the physical interaction devices) apt in terms of their affordances?

To this end, we propose a conceptual framework based on three components:

- a structured representation of the mappings holding between the metaphor source, the metaphor target, the interface and the digital system;
- a conceptual model for describing TUI metaphors, defining the components, structure and role of tangible interface elements and their relations with the digital application;
- three relevant properties that help designers to evaluate the quality of a metaphor reification in a tangible system with respect to the system components and to the metaphor definition.

The paper is organized as follows: in Sects. 2 and 3 we review the relevant literature related to TUIs and to the study of metaphors in language and Human Computer Interaction, identifying the concepts of TUI and the relations between the source and target of a metaphor, that are preponderant for describing and understanding a TUI metaphor. Section 4 formulates the problem and introduces a simple case study to highlight the need of a more structured approach for assessing metaphors in TUIs. In Sects. 5 and 6 we elaborate a conceptual framework to support the description and evaluation of metaphor reification in a tangible interface: Sect. 5 introduces a conceptual model for describing the mapping of a metaphor to an application interface, while in Sect. 6 the conceptual framework is enriched with the concepts of coherence, coverage and compliance that provide support for evaluating the mapping. In Sect. 7 we use this conceptual framework to discuss a more articulated case study evaluating the quality and potential of the involved metaphor implementation. We draw the concluding remarks in Sect. 8.

2 Tangible user interfaces

In order to provide a support for the analysis of metaphors in TUIs we first briefly present the domain and its evolutions. We then focus on the key characteristics of TUIs which a designer has to adjust depending on the goal and context of use. In our context these characteristics are a potential leverage to consider when implementing a metaphor in a TUI and will ground the remainder of the contribution.

Tangible user interfaces are interfaces in which users interact with a digital system through the manipulation of physical objects [37,72]. Appropriate devices, like sensors and actuators which build up the TUI implementation, interpret events occurring in the physical layer, translate these events into the digital domain and report to the users the results of the computations through a physical layer. Initially, due to the need of a more natural approach offered to user interaction, they have been studied as vehicles for children education in the context of learning by doing [57,60,70]. Their potential to support complex operations without specific computing skills stimulated their use to meet the requirements of demanding and constrained application domains such as surgery [50], air traffic control [52] and military applications [56]. They are now used in arts, knowledge transfer, communication, marketing, etc. and have largely demonstrated their potential benefits [67]. In the domain of TUIs models have been developed to describe such interactions and, although explicit references to metaphors are not mentioned, these models draw some parallels with real world properties and activities.

Hornecker and Buur [31] first highlight four major characteristics useful to describe TUIs: materiality, physical embodiment, embodied interaction, and place of the real space. On this basis they proposed a framework identifying different *themes*, perspectives to guide the analysis and design of TUI. The first theme, *Tangible Manipulation*, describes three main concepts relevant to the mapping of material representations onto different TUI aspects: *physical actions* that can be performed, *granularity* of interaction steps, and understandability of the *links* between physical and associated digital concepts or data. Additional themes refer to broader considerations such as embodiment in the real space and representations significance. This framework thus pinpoints generic properties of TUIs.

Reality-based interaction (RBI) [40] is an abstract model describing TUIs according to four dimensions related to real world properties that can be used to enhance the correspondence between the real world and the TUI or to better integrate a TUI in the real world: naïf physics (NP) refers to the knowledge about the physical world; body awareness and skills (BAS) denotes users' aptitude to use and move their bodies; environment awareness and skills (EAS) designates actions performed on the environment and physical artifacts it contains; social awareness and skills (SAS) stands for the set of human–human exchanges. Thus, this model promotes the analogy of the TUI rules with the rules of the physical world.

The token and constraint (TAC) model [73] is also referring to concepts of the real world domain to describe TUI. Physical objects involved are called *pyfos*; physical *constraints* are described and associated to each *pyfo*. Combining a *pyfo* to its constraints constitutes a *token* that can be associated to a range of possible digital data. TUI are thus described to ensure that the artifacts and constraints existing in the real world do match the concepts and constraints of the digital world.

The mixed interaction model (MIM) [20] considers digital system issues instead of focusing on the physical world only. This model characterizes the modalities bridging the physical and the digital worlds: pairs of device and language are specified to express how physical properties are linked to digital ones. Here the description highlights the software and technological solutions underlying the TUI: the model describes how the link between physical and digital worlds can be technologically supported.

An intermediate approach is adopted by the *ASUR* model [21]. It focuses on the interaction occurring between the user and the system. By identifying real physical entities (R), digital entities of the computer systems (S) and adapters (A) linking both worlds, interaction channels depict how these entities are combined to allow the user (U) to take advantage of tangible and mixed reality interfaces. In this model, the primary focus is on how the user has to behave or how the user's behavior is affected by the TUI: the adequacy of the user's behavior in the targeted interactive context can thus be measured.

Even if they adopt different points of view on TUIs, all the models presented above have in common a reference to six main categories of elements involved in the description of a TUI:

- P: elements of the *physical* world;
- D: elements of the *digital* world;

- B: elements of the *border* between the two worlds, i.e., sensors, effectors, other devices supporting the communication between physical and digital world;
- M: elements carrying *messages* over the border, such as communication languages, media, etc.;
- U: *users* of the TUI;
- A: *actions* that can be performed by users on physical elements.

Indeed, physical (P) and digital (D) objects, users (U) and actions (A) are intrinsic components of an interactive system seeking to merge the physical and digital worlds. By construction, a bridge is required over the two worlds to establish the exchange of data: technologies are required and are therefore positioned at the border (B) between these two worlds. Finally, to operate a computer based system, data need to be exchanged in the form of messages (M).

Table 1 compares such elements in the different models discussed. It can be noted that not all the models allow a complete coverage of the six categories. In particular, RBI is the model with the smallest coverage: messages and border are not covered by this model, because it focuses on the description of the interface and is not fundamentally concerned with the technological implementation of the interface: intrinsic characteristics and behavior are the most prominent consideration addressed by RBI. To the other extreme, MIM and ASUR are adopting a point of view centered on the interaction in which the characteristics of the underlying technological solutions are considered and linked with human, physical and digital considerations and constraints. TAC and Hornecker & Buur's model are in between these two extremes; they tend to cope with the components of TUI and how they act together, but not how they are technically supported and operated.

3 Metaphor

3.1 Metaphor in human language

The study of metaphors in interactive computer based systems cannot ignore the huge amount of work made in cognitive linguistics and psychology. Lakoff and Johnson have developed the conceptual metaphor theory (CMT) according to a view of the correspondence between concepts in a metaphor defined as a *mapping*, in the mathematical sense, between a *source domain* and a *target domain* [48,49].

They have analyzed a large set of metaphors, each identified by source and target domains (e.g., "ARGUMENT is WAR", in which ARGUMENT is the target and WAR the source), supporting subject understanding through analogies between the concepts of the two domains (e.g., "your claims are *indefensible*"). Metaphors involve different parts of a sentence, like nouns, verbs, adjectives, whose original meaning is tweaked to refer to concepts belonging to a different domain of interpretation.

Metaphors are also bound to the idea of *image-schemas* [33,34,41,47], abstract representations of recurring patterns coming from human experience, mainly bodily interaction and linguistic experience. While bound to the human experience in the physical world, they provide support for understanding abstract concepts. Examples of image-schemas are prototypes of common experience instances like object, containment, path, direction on which several common metaphors are grounded. Indeed, metaphors are useful to understand and evaluate a specific situation when the source domain is very close to our knowledge, involving concepts like space (e.g., position, motion, direction), time (e.g., speed, duration) and feelings (e.g., affection, opposition, contrast).

According to Lakoff and Johnson [49], metaphors are explained based on the idea of *coherence* between two

Table 1 TUI models comparison

Model	Physical	Digital	Border	Messages	User	Actions
Hornecker	Materiality	Digital data or concepts	N/A	Links between physical and digital concept	User	Physical actions
RBI	*NP* constitutes attributes of it	Computer functionalities	N/A	N/A	*SAS* and *BAS*: social and body involvement	*EAS*
TAC	Token (*pyfo* + constraints)	Digital data	N/A	Association between token and data	User	Physical constraints
MIM	Physical properties	Digital properties	Device	Languages and linking modalities	User element	Links between user and physical properties
ASUR	R entities	S entities	A entities	Interaction channels between A (or S) and S entities	U entity	Interaction channels between U and R entities

domains. The word *coherence* has an implicit meaning related to human experience: it is the property that gives a system of concepts and rules the ability to be understood in a systematic way rather than as a collection of isolated and random cases. To refine the concept of metaphor, Lakoff and Johnson identify three main classes of metaphors: *structural* metaphors, in which a target concept is explained and structured using terms and structure from a source domain; *orientational* metaphors, in which a whole system of concepts is organized with respect to one another, mostly according to spatial relations; *ontological* metaphors, which allow us to reason about events, activities, emotions, and so on. Orientational and ontological metaphors are indeed at the core of metaphorical interfaces since the complex set of operations that support interaction must be referred to a coherent interpretation in a specified domain; being linked to the human experience they allow reasoning, hence help understanding of interface behavior without explicit training.

Some proposals have been made to develop a formal theory of metaphor [36,45] and to match metaphor comprehension with computational systems [69,78]. Formal models help to classify different types of metaphors according to their syntactic and semantic role in the human language: the syntax defines to which part of discourse they apply: noun, adverb, verb, hence status, relation, action, etc.; the semantics defines which meaning they express.

3.2 Metaphor in HCI

The concept of metaphor has been successfully extended from the human language to the artificial languages used to interact with data and functions in computer based systems. Such extension, however, raises new issues. The base metaphor model used in HCI derives from the Peirce semiotic [26], linking in a threefold relation a concept, called *object*, a sign or symbol that represents the object in a synthetic way, called *representamen*, and an interpretation, called *intepretant*. A match between the *intepretant* and the *object* denotes a correct understanding of the *representamen*, i.e., the success of the metaphor.

In cognitive linguistics, the source and target metaphor domains are defined on the same semiotic base, i.e., the human language. In HCI the two domains are built on different semiotic codes: the user acts on an interface that is a representation (often visual) of some *model* of the digital operations' domain. Hence, a metaphor provides meaning to the interface by mapping the operations and tasks at one side onto the application program at the other side through a suitable *interpretation* by the user. Such interpretation must match the interpretation that suggested the interface design [3,10,11,68].

According to the conceptual metaphor theory (CMT) developed by Lakoff and Johnson a metaphor is more than a figure of speech: it is a *mode of thought*, in the sense that "metaphor can occur in other modes than language alone" [24, p. 4], the modes being, in such a context, written language, spoken language, static and moving images, music, non-verbal sound and gestures; such vision links the human communication research domain to the domain of multimodal interaction but jeopardizes the problems of finding a suitable interpretation for the use of metaphor.

Interaction metaphors have been extensively studied, covering applications ranging from information systems to hypermedia navigation and to educational applications [7,28,29,75]. A relevant issue in interaction metaphors is their intuitiveness which, according to Hurtienne and Blessing [33], is based on prior knowledge and subconscious application; intuitiveness is also a property of the interface, which might suggest or not the proper operations to execute an application; in a metaphorical interface also the choice of the metaphor impacts the interface use. Image schemas are thus a basis on which intuitive interface can be designed, since their understanding is part of the basic human experience [32,35].

As noted by Alty et al. [2, p. 202], "the literature has provided little guidance for the selection of appropriate interface metaphors." Also Bakker et al. [8, p. 436] note that "when new interactions are designed, rather than existing interactions redesigned, current literature offers few guidelines to the approach of such design processes." Nevertheless, some notable efforts to metaphoric interfaces design have been made.

Hints are given by Carroll and Mack [17], with reference to the learning environment, who introduce concepts like *base specificity*, *clarity*, *richness*, *abstractness*, and points out the *systematic* aspect of metaphors. Blackwell [15] discusses interface design and actions making concrete, i.e., visible, the metaphor behind the relations between the interface and the digital application.

A pragmatic methodology is applied to the design of an interface to an online messaging system named DOORS [4]; three metaphors are analyzed and the most suitable is identified by comparing the metaphor suggestions and the system functions. Alty et al. [1,2] define six major steps for engineering the interface design, based on the analysis of the metaphor mapping the interface to the system and vice versa. The analysis is based on the intersection between the features found in the digital system (S) and in the metaphor (M): $S+M+$ are features that exist both in the system and in the metaphor, corresponding to a match between the system and the metaphor; $S+M-$ are features that exist only in the system, showing the (partial) metaphor inadequacy; $S-M+$ are features that exist in the metaphor but not in the system, resulting in unresolved expectations induced by the metaphor.

Sajaniemi and Stützle [66] analyze three approaches to metaphor analysis: *operational approaches* focus on the effect that a metaphor has on learning new concepts; *pragmatic approaches* analyze how a metaphor is useful, i.e., it is well understood by users; *structural approaches* analyze the correspondence (similarities and dissimilarities) between the metaphor source and target.

Among the new issues raised by metaphors in HCI, an important point is that coherence is not the only relevant property. In cognitive linguistics, coherence is important to *reason* about metaphors, but in HCI the way a metaphor is implemented in an interface is also important: a metaphor is recognizable not only by its conceptual structure, but also through its implementation, e.g., through the correspondence between the concepts of the source domain and the way they are translated into the interface [15].

Metaphors are analyzed by Van Hees and Engelen [76] in the context of multimodal user interfaces, where they can support a smooth migration from one interaction modality to another. The cited work moves from the design of multimodal interfaces for sight impaired people to develop an approach based on abstract user interface descriptions referred to a unique consistent conceptual model called *parallel user interface rendering* (PUIR), from which multiple interaction modalities can be derived.

3.3 Metaphor in TUI

One of the goals of TUIs is to increase the naturalness of interaction. To this end the use of everyday objects to operate a digital systems is effective as long as their meaning is already known to the user. Apart the case in which the digital application duplicates the functions of a physical device, the interpretation of an interaction object's behavior depends on the relations between the physical object proper function and the functions assigned to it in the digital application domain. This correspondence is often grounded on a metaphor which, to be natural, should involve a source domain familiar to the user. The additional layer made of physical interaction objects present in TUIs between a user and a digital system, adds to the interaction space new opportunities for metaphors. Through the presence and the manipulation of a variety of physical objects related to the domain of the metaphor source, this layer multiplies the possibilities in terms of the metaphor reification into the interface.

Beyond the description of TUIs as presented in Sect. 2, other approaches are seeking to evaluate tangible interfaces. They are not explicitly referring to the term *metaphor* but are pinpointing aspects of the interface worth considering for designing good tangible experiences.

Underkoffler and Ishii [74] analyze the *luminous-tangible systems*, where the manipulation of physical objects is matched by the projection of visual information on and around the objects themselves. They identified a continuum of physical object meanings ranging from the objects *per se*, to representatives of their attributes and functions, up to their use as abstract tools. Koleva et al. [46] defined the *degree of coherence*: it is used to express to which extent physical and digital objects linked through the TUI are perceived as being the same. For example, an illusion of manipulating exactly the same object can exist, or be limited to a subset of attributes only; a physical object can just appear as a *proxy* for manipulation or as an identifier for data; physical objects can also just appear as tools.

Fishkin [23] elaborates a two dimensional taxonomy for analyzing TUIs. It characterizes the proximity existing between input and output modalities used in a TUI and the link existing between a physical action and the resulting effect on the digital domain. *Noun* and *Verb* are the two key terms of this taxonomy. As underlined by Oppl and Stary [59], these attempts to differentiate different forms of TUI emphasize the distinction between two aspects of TUIs: *appearance* and *behavior*. There is thus a trade-off between metaphors: (1) based solely on the appearance of TUI, (2) based on their action or usage, and (3) based on a combination of both. Such a trade-off has been used by Oppl and Stary to identify and validate appropriate TUI design specific to these three classes.

Such early emphasis on isomorphic mapping between physical and digital object on one hand and action effect on the other hand is somehow typical in HCI. But these approaches do not explicitly consider the potential meaning that can be covered by a metaphorical link. To overcome this limitation, adaptations of the *CMT*, recalled in Sect. 3.1, have been developed. Antle et al [5], Hurtienne and Israel [34] and more recently Macaranas et al. [51] extended CMT to TUI by extending the source of the pairing to physical concepts, including physical attributes and spatial properties.

However, TUI design is complex: many attributes and considerations are combined. As a result, potential metaphorical mappings based on a TUI are multiple. One attempt to cope with this diversity consists in structuring a TUI in three domains: physical, digital and application [53]. The two first domains are split into two sub-domains, *object* and *manipulation*, to fit with the common idea that TUI deals with appearance and behavior. Sources and targets of a metaphorical link may then be part of one of the domains or sub-domains. A new characterization of metaphor in TUI is thus raised, allowing the identification of design and implementation questions specific to each set of metaphors mappings [54]. To further highlight the potential diversity of sources, Hornecker [30] stressed that physical objects have potentially unlimited set of properties able to carry such a metaphorical mapping. Hornecker even underlines that physical properties may automatically trigger user's perception, understanding, behavior and expectations.

A people-centered iterative design approach to embodied metaphor-based interaction is suggested by Bakker et al. [8], who propose five phases starting with studies to identify applicable metaphors, continuing with the creation of low fidelity prototypes, their evaluation in terms of affordances supporting embodied schematic movements, and finally in their refinement into high fidelity interactive prototypes which could be evaluated in terms of embodied interactional mappings.

4 Introducing a conceptual framework for evaluating metaphor reification in TUIs

All the models discussed in Sect. 2 describe TUIs from different points of view, ranging from an almost engineering perspective (MIM) to a theoretical comparison with the reality (RBI), through the description of the induced interaction (ASUR) or specific physical dimensions (TAC, Hornecker and Buur's). They have been developed and studied to support the understanding of interface use, their benefits and the associated implementation issues. The presence of metaphors in the interface is not considered in these models, even if they embed concepts typical of the domain mapping offered by metaphors: for example, the mapping between the physical and digital domains is described but not evaluated for consistency in terms of interaction objects' *affordances*—which are, according to Norman [58], those action possibilities that are readily perceivable by a user—and *plausibility* with respect to the target digital operations.

In addition, most of the evaluation approaches discussed in Sect. 3.3 are not either referring to metaphor; they raise different design considerations and forms of TUI. They can thus be used to derive design hints and classification schemes, but do not focus on how TUIs match potential metaphors; the correspondence between the physical manipulation of the interface and the digital operations is usually assumed correct in terms of human experience, and analyzed and classified with reference to general ontologies often independent from the TUI design [23,71].

However, the evaluation of a TUI in terms of the subsumed metaphor is important in several contexts. One of the benefits of TUIs with respect to GUI based interaction is the possibility to have a more direct and immediate perception of the relations between the operations performed by the user and the corresponding digital operations [38]; this perception impacts the learning curve of a new product, allows users not trained in computer systems to successfully use digital applications and lessens the digital divide for people traditionally far from technical skill, such as children and elderly people, to cite only a few issues [60,70]. The presence of a clearly identifiable metaphor in an interface helps a user to approach new functions based on the understanding of the source side of the metaphor, close to the human experience.

Our contribution to the problem of analyzing metaphorical tangible interfaces is the description and evaluation of the correspondence between the metaphor and its implementation in a tangible interface for a digital application. Plausibility, ease of use and coherence are important in the perspective of a natural interaction style; but in a metaphorical context these three concepts depend on the way the metaphor is coherently applied and complete, i.e., on the degree of correspondence between the concepts and operations in the metaphor source with respect to its reification in the interface.

4.1 Framing our investigation space

The relations between the metaphor domain and a digital system are illustrated in Fig. 1, which shows four mappings. The metaphor defines a correspondence between the source and the target domains (1). The application interface implements the metaphor source (2): it represents the concepts of the metaphor source through elements of the interface. We can structure such relations at three levels:

- metaphor entities map to interface objects;
- metaphor actions map to actions on interface objects;
- object attributes map to attributes of interface objects.

The application implements the metaphor target domain (3), and is operated through the metaphorical interface. User manipulations applied to object of the interface map to (activate) functions of the application (4).

Mappings (2) and (4) are specifically relevant for our analysis: mapping (2) defines how the source metaphor is represented in the interface. Mapping (4) defines how the interface drives the application. Both contribute to the description

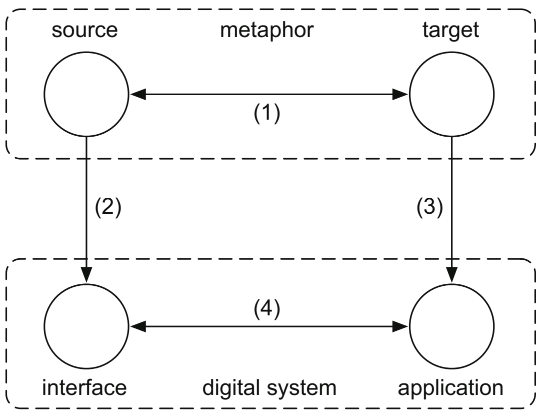

Fig. 1 Mappings between metaphor and digital application

and evaluation of a metaphorical interface because its quality is perceived through the behavior of the application. Mappings (1) and (3) are the result of design activities out of the scope of our analysis, even if they are important in the design and implementation of a correct application. Mapping (1) defines the metaphor itself, while mapping (3) defines how the application implements the requirements and specifications of the target domain, which is the domain in which the semantics of the application are exploited.

In the following of this paper we shall use the term *projection* to denote the mapping of the metaphor and its components (objects and actions) to the tangible system, which concretely defines the implementation of the metaphor source in the application interface and the implementation of the metaphor target in the application. As said in Sect. 1, the focus of this paper is the projection of the metaphor source on the tangible interface.

4.2 An introductory example

A discussion of a simple introductory example[1] helps understanding how to analyze the mapping between the source and target domains and how to check for metaphor consistency. The example is drawn and extended from two papers by Pittarello and Stecca [61,62] about the use of a set of geometric solids as a tangible interface to query an image database.

The paper describes and evaluates a tangible system for querying an image database by selecting three different image features: category (i.e., subject), denoted by a sample image, color type (colored or B&W) and brightness (from dark to bright). The image database system is operated through a tangible interface made of objects containing orientation sensors. Three of them are simple geometric solids: a cube, a plate and a cylinder, decorated with sample images and symbols, are used to compose a query. When placed on a table the upper face shows the values used as query attributes. A fourth object, a barrel, is used to execute the query and browse the retrieved images, shown in a video projection within a cartoon scenario. Combining the manipulation of physical objects with visual interpretation of the pictures on them and the projected imagery showing the query execution, this interface is indeed multimodal, even if the tangible components are prominent. The system was first tested with children in pre-scholar age.

While the authors' goal was to design a set of guidelines to map geometric properties to digital functions, such interface defines a quite evident metaphor which maps geometric solids to database attributes, solid types to data types and a group of solids to a query on several attributes. The cube,

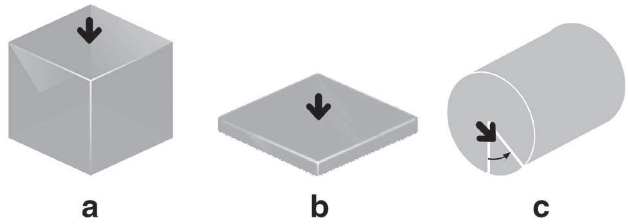

Fig. 2 The solids for the metaphoric interface setting values for discrete (**a**), binary (**b**) and continuous (**c**) query parameters

the cylinder and the plate metaphorically denote discrete, continuous and boolean variables. The barrel metaphorically denotes the interface for browsing the retrieved images. The system is thus a blend of two metaphors.

We analyze in detail these metaphors discussing the correspondence between the source (geometric solids composition) and the target (image database querying) domains.

- In the source domain (projected onto the tangible interface) three solids exist: a cube, a plate and a cylinder (Fig. 2). The solids are placed on a table, showing the image or symbol on the upper face as the one selected for the query. In the case of the cylinder, the rotation defines an angle in a 360° range.
- In the target domain the query parameters are denoted by three attributes respectively over discrete, binary and continuous values.
- A correspondence exists between the objects and their placement, and the query parameters values. The cube, the plate and the cylinder can take, respectively, a discrete number of different placements, a two-valued placement and a continuous range of placements. The attributes' values are set according to the objects' position.
- A fourth object, a barrel, is used to actually execute the query and to browse the results; it will be described separately.

Additional rules are imposed by the tangible interface components: (1) a discrete attribute can hold (at most) six values; (2) a continuous attribute can hold values in a range expressed as a normalized percentage with respect to conventional minimum and maximum values; (3) there are no null values since all configurations of objects are meaningful. A few more assumptions in the target domain must be done, which do not impact the metaphor but make it more complete: (4) there is only one database, since the operation has an implicit target; (5) the dynamics of the objects during placement (e.g., trajectory, motion, speed) and their order on the table is not relevant; (6) there is an implicit AND connection between query parameters; this point is justified by the presence of all the objects on the table at the same time.

[1] This section and part of Sect. 5 have been published in a preliminary form in [18].

By extending the scenario discussed by Pittarello and Stecca, we note that several instances of the same solid could exist, which should be considered unrelated as long as each is distinguishable. In the target domain the query could thus be composed by several independent parameters of a same type. Other polyhedra with different numbers of faces could also be used (as long as their geometry allows correct and stable placements) which could correspond to attributes of different cardinality.

Query execution and image browsing are supported by the *barrel*. It is moved and tilted as to "pour" its content into a basin (query execution), and rolled to browse the returned images. Tapping the barrel's top selects the current image which is enlarged on the screen. For the barrel the following analysis of the metaphor holds.

- A barrel contains some stuff, often a fluid; it can be empty. The barrel can be rolled, and the content can flow from the barrel if tilted.
- A query result contains some data (possibly none), which can be shown to the user and browsed sequentially (according to an unspecified sorting order).
- In the metaphor, query results are shown by pouring the barrel content, and are browsed by rotating the barrel, so a correspondence exists between the use of the barrel and the operations on queried images.

This part of the metaphor, even if coherent in terms of data operations, is weaker from the objects' affordances perspective; the authors note in their papers that children experienced some difficulties in this phase of the experiment. One of the reasons, in our opinion, is that while pouring the barrel's content is a plausible metaphor for extracting the query results, rolling and tapping have a weak correspondence with the target actions. A different metaphor, e.g., tilting the barrel to void it into a container and moving the container back and forth would have been, perhaps, more appropriate even if more complex from an operational point of view.

This example raises some issues related to metaphor structure and interpretation. It shows that many relations exist within a metaphor and an interface implementing it: between objects, between operations, between rules and systems. For example, the suggestion of an AND conjunction between the query parameters, even if not directly deriving from the properties of the objects involved, is consistent with the concept of keeping many objects together.

5 Defining a conceptual model for TUI metaphor description

Language metaphors have been analyzed to understand how they can be identified in a systematic way by a group of scholars called Pragglejaz [64], resulting in a method called *metaphor identification procedure* (MIP). The method proceeds through four phases: a reading of the text to understand its general meaning, a collection of its lexical units, the analysis of the lexical components to evaluate if they carry a literal or metaphorical meaning, and a final classification. The third phase, the most important, relies on the evaluation if the meaning of a lexical unit has more value (e.g., it is more easily understood and coherent with the sentence) in a context different from the context of the whole text: for example, it is more concrete in another context, or more precise, or related to a bodily action or to a historical period; in these cases the lexical unit is marked as being metaphorical.

The method grounds on three concepts: that words may have several meanings or interpretations according to the context, that plausible interpretations are defined both by the narrow context in which the words appear (the sentence) and the general theme of the discourse, and that the relations between the narrow context and the general context define the presence or not of a metaphor.

In the context of TUIs the units of analysis are not words but physical objects and actions in the physical environment. A metaphor is defined when their use is normally referring to a different context than the one suggested by the application. As in language, the metaphor relies on different levels; at the single object level (components of the interface), at their combination (how they are related and structured), and how they must be operated in the context of the application by reference to a different, more familiar to the user, domain (a semantic level).

To offer a structured reference useful to elicit and describe the relations between a tangible interface and the subsuming metaphor, we first present a model expressing how a metaphor is projected into a tangible interface, i.e., which parts of the tangible interface are related to which concepts of the metaphor. Beyond the definition and illustration of this model, we also draw a clear link between the elements of this model, the major elements identified in Sect. 2 as constitutive of a tangible interface and the concepts considered by existing models of tangible interface. As such, our model is intended to constitute an original support for describing the implementation of a metaphor into a TUI, while being anchored in the TUI design models and properties established in the literature.

5.1 Projecting a metaphor onto a tangible interface

The digital application is operated by input functions interfacing the digital application, which computes the results. In the tangible interface artifacts are manipulated by the user (in input) and by the system (in output); operating an input artifact causes a state change in the application and, possibly, some perceptible results which are conveyed through the

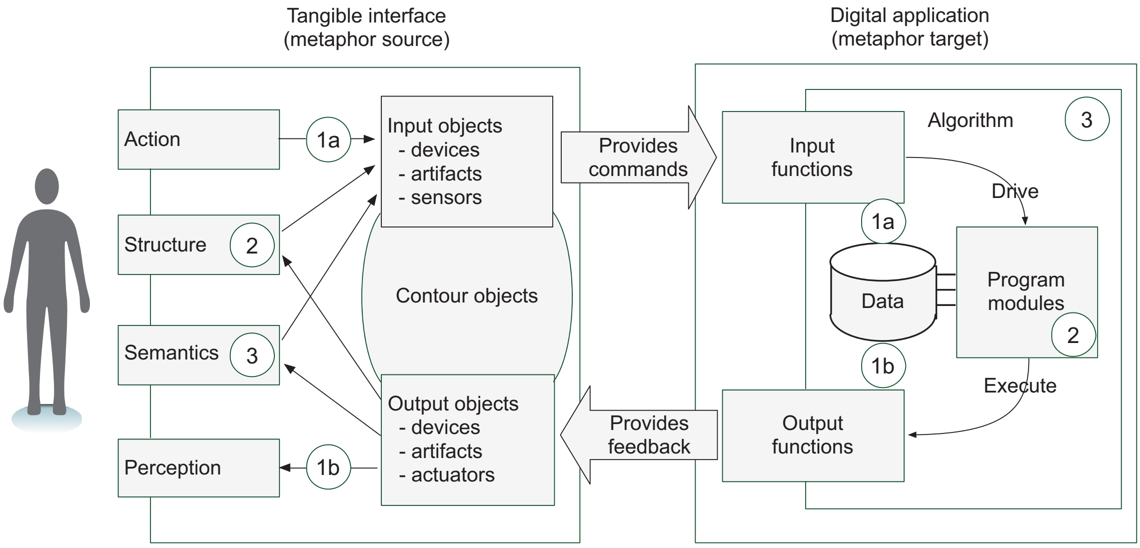

Fig. 3 A TUI description supporting metaphor analysis and evaluation

output artifacts. In the cases where the interface is built on a metaphor, its components and behaviors should be interpreted according to the concepts of the metaphor source and the mapping between the concepts defined in the metaphor source and target domains. To refine the description of such relations we introduce a number of entities; they form a conceptual model intended to describe how the metaphor, the interface and the digital system are linked together.

With reference to Fig. 3, in the interface, which implements the metaphor source:

- *input objects* include *physical artifacts* and *devices* operated by a user to act upon the system, and *sensors* capturing environment conditions (including physical artifacts positions and orientation) and changes in controlled parameters produced by the user;
- *output objects* are perceptual *devices*, *actuators* and the perceptual information generated by the physical *artifacts* driven by the application; the output objects are used to reflect the state of the system. A same object can serve for both input and output, as, e.g., a mobile device with a touch display. Since many systems are provided with a tangible interface for input and a visual interface for output (often rich and realistic, but non composed of physical objects), we consider also the perceptual information generated by the application and presented by the interface as part of output objects, even if a strict definition would admit as *objects* only the physical devices used for the visualization;
- additional *contour objects* can be used to complete the perception of the system state, but are not necessarily related to the computation; they are part of the "aesthetics" of the interface, such as environment components, backgrounds, textures, models of a part of a real world, and give a sense of completeness, presence and reality to the scene. The contour objects have no role in fulfilling the specifications of the digital application.

In the digital system, which implements the metaphor target:

- *input functions* convey data to the digital application;
- *output functions* convey results (computed values and state changes) to the user through the interface;
- the *program* implements the digital application: it is the union of an algorithm and a set of *data* defining the program state; the program is usually decomposed into *modules* according to a structure suitable for the problem to be solved;

The user interacts with the tangible interface by issuing *actions*, composed according to some *structure* and provided with *semantic* meanings related to the metaphor. In return, the user *perceives* the computation results carried by the output objects.

This model describes an interactive tangible system also independently of the presence of a metaphor: its components describe how the interface maps to the digital application. The decomposition into objects and functions, and the relations among them, are however targeted to supporting interface analysis and evaluation when a subsuming metaphor is present. The model makes explicit which component of the interface implements which concept of the metaphor and corresponds to which component of the digital application. Table 2 classifies the components of the example of Sect. 4.2 according to this model.

Table 2 Elements of the example

Interface	
Input objects	Geometric solids, barrel, position sensors
Output objects	Projector, projected scene
Contour objects	Table, elements of the projection in cartoon style
Application	
Input functions	Parameter value assignment, query posing, result browsing, image selection
Output functions	Display image list, display selected image, scroll images
Program	Query execution, image retrieval, result ordering, etc

To refine the description of these relationships in a metaphorical interface we adopt the three traditional levels that distinguish the lexical, syntactic and semantic analysis. These three levels are associated to the components denoted by the circled numbers in Fig. 3.

At the *component level*, objects and functions are mapped such that the manipulation of input objects causes input functions to be executed (1a), and the execution of output functions changes the state of output objects (1b). The mapping depends on the metaphorical meaning given to the physical interface, and links concepts of the two domains at a low level. For example, Durrel Bishop's *marble answering machine* [63], one of the first design examples of TUIs, is based on a metaphor associating marbles with messages and the action of putting them on a plate with the action of listening to them or calling back the caller.

At the *structure level* (2), the structure of input objects and their relations define the amount, type, sequence and composition of actions that can be done on them to execute in a consistent way the digital application modules required to accomplish a meaningful task. For example, the marbles in the *marble answering machine* are simple objects, so the actions are limited to picking them and placing them onto a responsive place.

Conversely, the *ReacTable* [42] uses a set of physical objects marked with abstract symbols related to electric circuitry for audio processing. The objects are placed on a sensible surface and linked by virtual connections, to build virtual circuits producing music and audio effects. The input objects correspond to commands whose effect on the digital application is defined not only by their own functions but also by their mutual relations: signals are processed according to a complex system of interconnected generators and filters built by linking symbols together, influencing the way sound is produced and modulated.

At the *semantic level* (3) the digital application is understood and exercised by the user by interpreting the problem to be solved through the tangible interface, i.e., through its system of rules, goals and meanings. As an example, in the *Augmented Urban Planning Workbench* [39], the tangible interface elements are *models* of buildings placed on a sensitive table to drive a urban planning application. The models selection and placement in the scene is done according to the rules of the architecture domain, with proper spacing and orientation defined in terms of city planning goals and practices.

The manipulation actions considered refer to the expected behavior as defined in the *Function–Behavior–Structure* framework [25]; it depicts the set of actions that are expected to be derived from the structure of the object taken out of the metaphor domain, and not all the possible derived actions.

5.2 Linking TUI elements to the conceptual model

We now draw a parallel between the six categories of elements constituting a TUI (in *italics*) introduced in Sect. 2 and the elements of our conceptual model (in sans serif). Figure 4 draws a parallel between these two approaches and thus rewrites Fig. 3.

(*P*) Elements of the *physical world*. In our model they clearly refer to the artifacts in the input and output objects of the tangible interface. The contour objects of our model are also part of the *physical world*.

(*D*) Elements of the *digital world*. They straightforwardly refer to the elements of the digital application: input and output functions, algorithms, program modules and data. This part of the system is supposed to implement the target domain of the metaphor.

(*B*) Elements of the *border*. They are expressed in our model through the devices, sensors and actuators present as part of the input and output objects.

(*M*) Exchange of *messages*. They are present in our model between the tangible interface and the digital application to provide commands and feedback. Internal messages are also sent and received to the digital system between the modules and the required data.

(*U*) The *user*. Quite obviously, the user (U) is perfectly represented with its goal, knowledge, skills, limits and attributes.

(*A*) The user's *actions*. They are the actions performed by the user on the artifacts and the attributes of the artifacts themselves. Conversely, they also cover the user's perception of the system output.

The model provides three added features. First is the ability to distinguish different types of messages by specifying what is related to issuing commands from receiving the system's output. This is important to refine the analysis of the metaphor projection onto the tangible interface because it

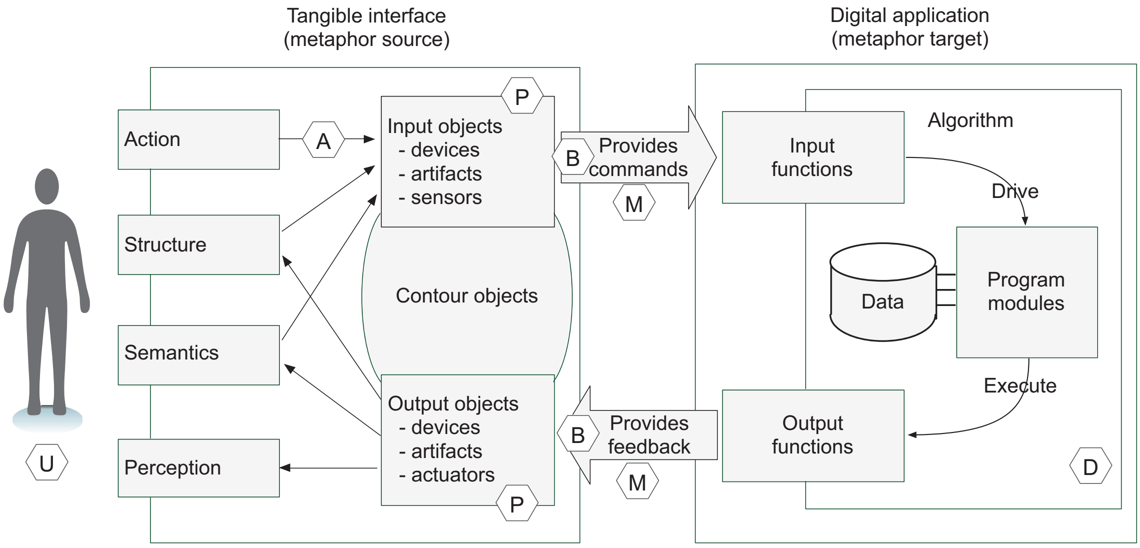

Fig. 4 Relations between metaphor and TUI components

takes into consideration separately the sources and targets of the messages and actions.

Second, our model emphasizes two additional considerations at the level of the tangible interfaces: structure and semantics. This is also very important with regards to the analysis of the metaphor projection onto a TUI as it identifies the several places where the metaphor applies.

Third, in the *P* class of elements it is useful to create a distinction between physical objects involved by the projection of the metaphor onto the interface (the artifacts) and any other domain (identified, e.g., by the contour objects).

Finally, by describing the metaphor projection onto a tangible interface, relationships between concepts of the models and design concepts used in TUI design models and approaches have been explicitly established. When exploring with our model the relevance of a metaphor projection, it is therefore easily feasible to momentarily switch the design focus to TUI intrinsic considerations potentially relevant to optimize the TUI design and consequently its implementation.

5.3 Comparing TUI models

We compare our model with the models supporting the description of TUI and summarized in Sect. 2.

From Hornecker & Buur's framework, the tangible manipulation perspective is pinpointing the same set of considerations than we aim to do when describing a TUI or modeling the metaphors it proposes. More general considerations such as space, embodiment and expressiveness of the representations are not yet directly considered in our model: they clearly refer to and refine some of the elements involved in the tangible interface, more specifically input/output objects and their manipulation, structure and semantics.

In the RBI model, naïf physics (NP) expresses useful characteristics of input and output objects; environment awareness and skills (EAS) clearly refer to the actions a user can apply on the input objects, while *SAS* and *BAS* (respectively social and body awareness and skills) refine the user, its context and additional contour objects. RBI is thus primarily centered on elements of the tangible interface depicted in our model.

Regarding the token and constraint (TAC) paradigm, *pyfo* and its constraints refer to the input and output objects of our model and their structure, while TAC represents a mapping from the input objects to the program through the input functions (or conversely in output).

In the MIM, input objects of our model are refined with the physical properties expressed in that model. Digital properties of MIM correspond to the parameters of the input and output functions and to the data of our model. MIM modalities describe how a message is transferred from the tangible interface to the application and vice versa: it includes the device that operates this exchange and the commands and feedbacks.

Finally, regarding the ASUR model, artifacts of our model are more finely described by the real objects in ASUR. Input functions and the program are together included in the systems components, while ASUR adaptors correspond to the devices, sensors and actuators of the input and output objects in our model. This refines the description provided by TAC at a technological level.

To conclude, our conceptual model for describing the projection of metaphors on TUIs relates to the main components that build up a TUI. As we just highlighted, our conceptual model is consistent with the different models of TUIs discussed in the literature. It is therefore addressing TUI specificities in terms of materiality, interactions nature, components and technology. While the terminology we are using is close to the terminology of the ASUR model, we prefer to keep it distinct from any specific terminology used by other models in order to remain neutral and independent of the TUI specific model. Indeed, our conceptual approach is dedicated to the description or the metaphor projection on TUI. The other models are dedicated to the design of TUI in general, each of them offering a specificity on TUI design. Having established a link between those models and our own model allows to keep the specificities and benefits of each approach while providing a support to switch from one design resource to another, e.g. from one TUI specific design consideration to another, including the metaphor projection.

6 Evaluating metaphor implementation in tangible interfaces

In order to go beyond the description of the projection of the metaphor into TUI, we extend our conceptual framework to reason about the quality of such projection, hence of the metaphor implementation.

We frame our evaluation on three properties: coherence, coverage and compliance. These three properties are related to three key aspects of the metaphor projection onto a tangible interface: how coherently the metaphor is projected onto the interface, how complete is the projection, and at what extent the metaphor is recognizable in the objects used during interaction, in their affordances and in their relations.

We do not claim that these properties must always be obeyed in any metaphorical tangible system; but, according to the context, such considerations and their expression in the terms of TUI components are helpful to orient good design and to evaluate the appropriateness of the metaphor implementation in the chosen interface. The following paragraphs address each of these three properties. We provide a definition and detail how the property can be expressed with respect to the model we have introduced above. Finally we refer the properties to the example of Sect. 4.2.

6.1 Coherence

In TUI—as well as in HCI—the mapping between the two metaphor sides is the result of an explicit design action, hence it is subject to a certain degree of subjectivity which may lead to a more or less appropriate choice of the metaphor and of its implementation. Indeed, in the context of language metaphor, coherence is a basic, unexplained concept, relying on intuitive understanding. For example, *Oxford Dictionaries Online*[2] defines coherence as "the quality of being logical and consistent", where *consistent* means "not containing any logical contradiction". When analyzing interaction metaphors, especially in TUI where the interface may have a complex meaning related to the physical human experience, evaluating if the tangible interface is an appropriate and *coherent* (in the sense used by Lakoff and Johnson) implementation of the metaphor remains one of the prominent issues. But such an implicit notion of coherence must be grounded on the relations between the interface and the digital application components.

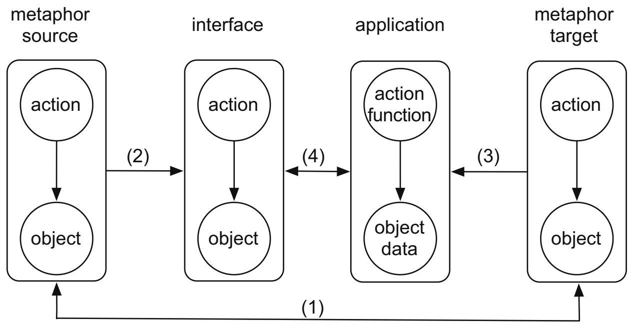

Fig. 5 Coherence among metaphor, interface and application

Figure 5 extends Fig. 1 by showing the relations between actions and objects which should be preserved by the metaphor implementation. The numbers on the arrows denoting mappings and projections correspond to those in Fig. 1. With reference to Fig. 5, in the context of metaphorical interfaces *coherence* is defined as the correspondence between the elements of the interface and the concepts of the metaphor source, compared to the correspondence between the concepts of the metaphor target and their implementation in the digital application. Concepts of the metaphor and elements of the digital application and its interface both include two different types of entities: actions and objects (functions and data). Moreover, a metaphor projection is coherent when the relations between the metaphor source and target are preserved in the implementation, i.e. between the interface and the application.

With reference to the levels discussed in Sect. 5.1, coherence exists at the *component* level if the mappings between objects and digital items, and between actions and functions, preserve their mutual relations; i.e., an action on an object in the tangible interface corresponds to the application of the function matching the action to the digital item matching the object.

At the *structure* level, coherence is assured if sequences or groups of actions on input objects which are consistent with the metaphor source interpretation produce sequences or groups of changes on the application state consistent with the metaphor target interpretation.

At the *semantic* level, a formal definition of coherence is problematic: at one side, it should derive from the metaphor components and their relations; at the other side, it implies

[2] http://www.oxforddictionaries.com.

concepts like plausibility, appropriateness, accuracy, etc., which belong to the metaphor as a whole. As such, its evaluation depends on how users globally perceive the relations between concepts of the interface and the application domains.

The example in Sect. 4.2 is coherent at the component level because in the metaphor geometric objects correspond to query parameters, and in its implementation orienting the solids corresponds to setting the parameters' values; it is also coherent at the structure level, because both solids and query parameters are independent each other, and the sequence of actions between query parameters setting and query execution is preserved. At the semantic level the formulation of a query corresponds to the positioning of the objects by exposing in their upper face the wanted value (the right angle for the cylinder) which is coherent with the selection of only one value for each parameters according to the parameters type: discrete, continuous, two-valued.

6.2 Coverage

We can also question the *coverage* of a metaphor projection onto a tangible interface: language metaphors are often incomplete, relying only on a few interesting concepts from the two sides, the remainder of the two knowledge environments being not relevant [49]. Coverage can play a role in interactive systems in helping a user to anticipate the behavior of unknown actions, given the actions already known. It is defined as a measure of the amount of concepts borrowed by the metaphor source, implemented in the tangible interface and used in the application. It is inspired by the concept of "conceptual baggage" [1,2,4] which represents "the proportion of features in a metaphor which do not map system functionality compared with those which do" [1, p. 309]: the main difference is that we compare the metaphor source and its projection onto the interface at a detailed level concerning objects and features of the tangible interface. As mentioned in Sect. 5.1, we only refer to concepts and actions related to the behavior of the user relevant for the application's goals, as defined by Gero [25].

With regards to our model, the coverage of the projection is based on: (1) how many concepts of the metaphor source are implemented as input objects in the TUI, that activate one or more input functions in a deterministic way; (2) conversely, how many input functions corresponding to operations defined in the metaphor source can be activated in a deterministic way by one or more input objects; (3) how many different results of computation map to different states of output objects representing the effect on the metaphor source;[3] (4) how many concepts of the metaphor identified by output objects are modified by at least one output function. We must note that an extensive coverage is hardly obtained, like in language metaphors; blends usually occur, and the knowledge domains on which the metaphors are based may be very large, while the interface implementation covers a well defined set of actions with a defined sets of objects relevant for the digital application.

In the example of Sect. 4.2 the coverage is very ample, because all placements and orientations of the geometric objects—when considering only the expected behaviors, i.e. the ones supposedly detected by the system—are meaningful and correspond to setting parameters values for any object and any value. The query execution phase is also well covered by the interface, because all the manipulation of the barrel are meaningful, as long as they are executed after the composition of the query. Other epistemic user's actions such as grouping tangible objects, taking them out of the tracking area, etc., are not part of the expected behavior and therefore not considered when evaluating the coverage.

6.3 Compliance

Finally, we can ask if the metaphor projection onto the tangible interface is *compliant*, i.e., *plausible* in terms of the translation of meaning from objects and actions of the interface to the source metaphor, grounding the plausibility, among other issues, on the affordances of objects to suggest a use.

With regards to our model, the projection is compliant if the structure and use of the tangible interface input objects meet their affordances according to the user's knowledge in the source metaphor domain.

In the example of Sect. 4.2 the part of interface concerning the query formulation with the solids is compliant with the solids' affordances, which suggest to place them on the table to clearly show the wanted image features, and placing the solids to show the parameter selection on the upper face is the most natural choice for a user. For the barrel, as we have already noted, the compliance is lower and is affected by some conventions about its use which do not correspond to the way a real barrel is used to pour its content.

6.4 Assessment of the conceptual framework

The conceptual framework we have presented in previous sections includes a structured representation of the relations between a metaphor and an interactive application, a conceptual model for describing the metaphor projection into a tangible system and a set of properties for supporting the reasoning about the quality of such projection. Assessing the validity of this framework could thus rely on the analysis of how designers take advantage of it, how different are the

[3] We consider only differences relevant in terms of feedback to the user; e.g., a different computed result not returned to the user for subsequent interaction is not considered relevant in the metaphor analysis.

design results with and without the use of the framework, how the implementation process is impacted, etc. Answering these questions with a quantitative approach requires an experimental protocol in which several parameters need to be seriously controlled and balanced: case studies, participants' knowledge, expertise with the framework, etc., resulting in a complex activity difficult to generalize to an entire class of cases like those offered by tangible interfaces. Moreover, not all the environments addressed by the framework are suitable for an experimental evaluation: we formalize the relations between a metaphor and an interface in order to describe how the metaphor is implemented, but do not address the quality of the metaphor itself, even if for a user the perception of the interface quality depends on both aspects.

Other attempts to create models of metaphor in HCI were also facing the question of the evaluation, and were solving it with a qualitative albeit accurate methodology. To establish the validity of their approach to interface metaphor design, based on the comparison between the metaphor and system features [4], Alty and Knott [1] applied it to several use cases, thus revealing different types of weakness and possible improvements. The validation of the workflow model proposed by Maquil et al. [53] is based on the assumption that it guides the exploration of the design space and supports a better understanding of the impact of the design choices.

Establishing the ability of a model to describe different use cases, to reveal differences and help discovering new design is exactly the goal covered by the three properties introduced by Beaudouin-Lafon [13] for evaluating interaction models: descriptive power, evaluative power and generative power. Such properties have been used by some authors [20,43] to evaluate the quality of interaction and interface models, and have proved to be effective in such evaluation independently from specific instances, which are anyway used as confirming test cases. In the following of this section we shall use these three properties to assess the validity of our conceptual framework.

According to Beaudouin-Lafon, the *descriptive power* of a design resource characterizes its ability to describe a significant range of different solutions covered by the considered design framework. Our conceptual framework contributes to the description dimension through its first part, i.e., the conceptual model. Indeed, our model captures the characteristics of the metaphor implementation in a TUI at a higher level than a software description approach would achieve. In addition our model offers a unified view of the implementation of a metaphor and as a result allows to describe in a systematic way the components of a tangible interface that reflect into the metaphor implementation, their role in the user-system communication as devices and artifacts for carrying input actions and data and output feedback and information, and their links with the components of the application logic and its structure.

The descriptive power of our conceptual framework has also been strengthened through the clear identification of bridges between the concepts of our analytical framework and existing TUI design models (Sect. 5.2). This provides a comprehensive list of existing axes that are either covered by our conceptual framework or outside its scope, thus better framing the range of design alternatives and specificities that can be described with it. As a result it shows how our conceptual framework unifies and extends previous frameworks but also where it enriches the existing approaches.

The *evaluative* or *comparative power* characterizes the conceptual framework's ability to assess and differentiate multiple design alternatives, and most often relies on the existence of metrics for comparing alternative designs [12]. While the choice and design of a suitable interaction metaphor is an activity out of the scope of our work (as specified in Sect. 4.1), its implementation in a specific interface must preserve a set of relations that can be discriminated and evaluated according to our conceptual model and to the three properties described above. Our framework helps designers and developers to examine whether the TUI interface fulfills the metaphor requirement. Indeed, the third part of our conceptual framework includes three properties that contribute to the evaluation of the metaphor projection quality.

As mentioned in Sect. 5.2, we are able to express sources and types of messages of different nature and differentiate them; the TUI level (structure, semantics) targeted by the metaphor projection can also vary. These elements are therefore contributing to the evaluative power of our analytical framework.

The *generative power* describes the ability of the design framework to create new designs. Several aspects of our framework effectively helps the designer in generating solutions. Obviously, by enforcing the identification of actions and structure of the involved input objects, the conceptual model suggests elements of the design to replace or optimize. Furthermore, as underlined in Fig. 3 commands are supposed to be issued by these input objects as a results of actions performed on them or of their structure: the conceptual model thus reveals explicitly the connection that already exist in the design solution and also suggest potential sources of commands that could be added in the design. The same design support is provided by the conceptual framework with the output objects. Beyond this first set of generative power, the properties described above do not only contribute to the assessment of the metaphor implementation: they also constitute leverages that assist the designer to design different metaphor based interactions to accomplish a set of tasks. By identifying the most important property to respect, the designer has the possibility to revisit the elements of the conceptual models involved in this property and thus adjust, optimize or redefine the design of the solution. This is thus a way to support the generative power of our conceptual framework.

7 A case study description and evaluation

7.1 A tangible museum installation about living species classification

We apply our framework to a non trivial case study coming from a project carried on with the Museum of Toulouse related to explaining *cladistics*, a modern method for the classification of living species [27].

In cladistics, a species is no longer a group deriving from another group, with similarities/differences between each other. Instead, cladistics takes into account the evolution of phylogenetic criteria over time. A phylogenetic criterion refers to different features related not to morphology but to functionality, such as having a dorsal nervous system, or a spiral growth, etc. A species is therefore a group for which a set of common criteria can be identified.

The representation of this classification is based on *cladograms*, hierarchical structures which show, at different nested level, the phylogenesis of the living species (Fig. 6).

For example, cat, human and chimpanzee are three species part of the same cladistic group because the three of them have fur and placenta. This also clearly states that the human is not the successor or the evolution of the chimpanzee, nor vice versa. Conversely, although they all have four legs, frogs, turtle, crocodile and cat do not constitute a valid group in cladistic, because the common ancestor they share is the fact that they have paws, and this group also includes human, chimpanzee and viper (in a receded form).

To present this new classification method to the visitors, a section of the Museum of Toulouse has a series of informative panels and a large static installation showing, on a wall, a cladogram with features attached to intermediate nodes and valid groups of living beings at branches end points. In addition, a co-design process involving computer scientist, museographers and paleontologists led to the implementation of an interactive application called *MIME*, *mixed interaction for museum environment*, highlighting the relationship

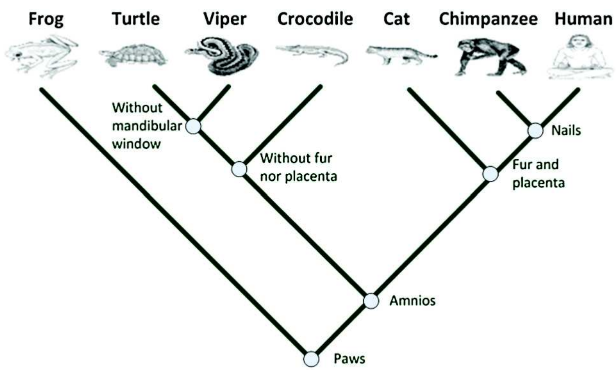

Fig. 6 A simple cladogram

between species and phylogenetic criteria. Field and lab studies focusing on performance and user's satisfaction have been performed on MIME to assess its impact on a museum visit [16,22].

7.2 A metaphor for cladogram representation and exploration

To promote the active involvement of the visitors, the MIME authors have conformed to Wagensberg's principles for a total museum [77]), and have proposed an installation with a metaphoric tangible interface to learn the phylogenetic criteria of the different living species. The installation is based on a metaphoric representation of a cladogram, conforming to its structure and hierarchy, and a way to explore it progressively highlighting the life evolution. On overall, the interaction metaphor is based on an *explorer* moving in an unknown environment, a complex building representing the cladogram, using a handheld physical device to move and to display the cladogram representation as it is discovered.

7.2.1 Cladogram representation

Being the cladogram a hierarchical structure, the chosen metaphoric 3D representation is a complex building made of hallways and rooms organized as a tree-like structure. Hallways correspond to branches in the cladogram while rooms represent nodes. The building and the surrounding environment are rendered as a 3D world projected on the museum's wall. Figure 7.1 shows an external overview of the structure, but navigation is only permitted inside this environment, i.e., along the cladogram branches. When the visitor reaches a room (Fig. 7.2), he/she is facing several doors leading to different hallways and an information panel. When approaching a door, the door can be opened and information about the destination of the hallway is displayed (Fig. 7.3)

The cladogram representation metaphor is based on the following elements:

- In the metaphor target domain, a cladogram is a tree structure; the root represents the totality of living beings; nodes identify phylogenetic criteria shared by all the species of the tree placed above this node[4] and are named by the criteria; leaves denote species.
- In the metaphor source domain, a complex building exists with rooms connected by hallways forming hierarchical connections; in each room an panel describes the room.
- A correspondence exists between the cladogram and the metaphor source, which is projected in the digital system interface: nodes are rooms, each corresponding to a phylogenetic criterion, and branches are hallways; node

[4] Cladograms are usually represented with the root at the bottom.

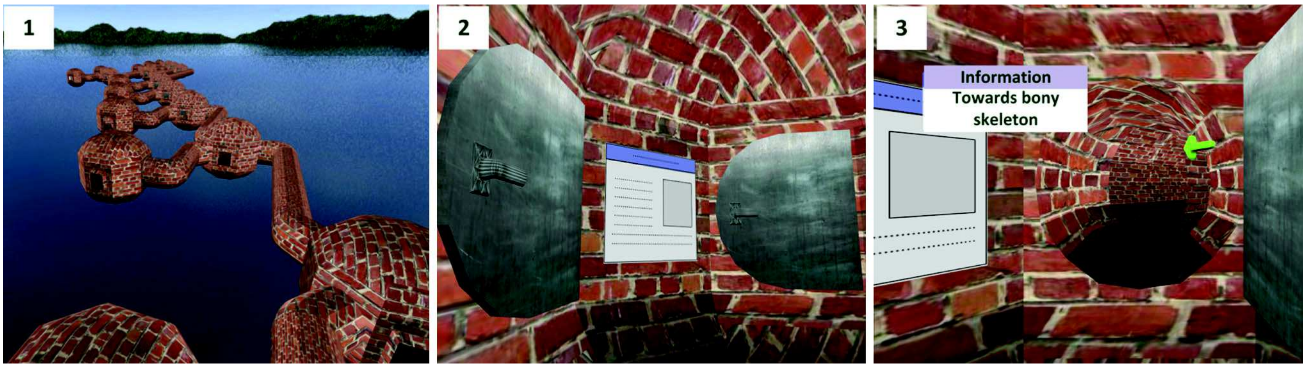

Fig. 7 The 3D representation of a cladogram adopted in MIME: *1* a view of the structure; *2* a room; *3* a panel explaining a branch destination

labels are informative panels describing the phylogenetic criteria. Rooms and hallways are connected according to the cladogram's hierarchical structure.

- The metaphoric source domain contains also entities, such as windows and doors, which are not strictly part of the cladogram metaphor (they are contour objects according to our model) but are indeed more than a simple decoration. Windows allow visitors to have a glance on the whole structure of the cladogram representation (e.g., its extension) but do not allow them to see the information associated to nodes and branches, which must be progressively discovered only by navigating the structure. Each hallway departing from a room and going up in the cladogram is closed by a door that must be opened to proceed, to explore the cladogram in a stepwise way; when returning back to previous levels of the cladogram, open doors reveal cladogram branches already explored.

7.2.2 Cladogram exploration

To discover the attributes of a species, the visitor (an explorer) must start from the cladogram root (must enter the metaphorical building), select a branch giving a value to the current phylogenetic criterion, walk the branch (the hallway) to the next criterion, continuing this way until a species is reached (a room with no exit). The information collected through the path is the set of values of the phylogenetic criteria characterizing that species.

Since the cladogram structure is initially unknown and progressively uncovered, the exploration metaphor is built around an interface made with a *flashlight*, a physical device that enlightens the explorer's walk as he/she proceeds in the building, supporting different actions. When entering a room, the explorer turns the flashlight around to point at the room content: the panel, the incoming hallway, the outgoing hallways, the doors. By moving the flashlight forward or upward, the explorer moves towards the pointed element: if it is the panel, the explorer approaches and reads the text; if it is an open hallway, the explorer enters and walks until the next room; a backward or down flashlight motion steps the explorer back from panels and windows.

The flashlight is also carrying a second metaphor (it is a *blend*): it can act as a *handle*; in front of a closed door it can be rotated to open the door. *Overloading* an interface object with more than one meaning is generally not desirable, but it has been done for practical purposes to keep the interface in a unique device. This choice will be discussed later, at the end of Sect. 7.4.

The graphical representation projected on the wall in front of the visitor is animated to give a more pleasant look to the journey, but the actual animation has no special meaning; the scene decoration appears indeed as a contour object in terms of the model of Fig. 3. Even if it is not relevant in terms of metaphor mapping onto the interface, it is important to give the user a sense of naturalness and completeness of the metaphor and to engage him/her in the exploration.

The detection of the flashlight position and orientation, the only information transferred from the interface to the digital system, is supported by a magnetic tracking device with six degrees of freedom.

7.3 Metaphor projection on the MIME interactive application

In this section we provide a systematic view of the metaphor projection in terms of the conceptual model introduced in Sect. 5 and illustrated in Fig. 3. It results into identifying input, output and contour objects of the interface (the metaphor source), input and output functions and the program in the digital application (metaphor target).

In terms of input objects, two objects are involved in the installation interface. One is an *artifact*, the flashlight, whose relevant attributes are its motion and orientation and a button to switch it on and off. The second is a position *sensor*, made of two parts: the emitting part is used to define its position and orientation; the receiving part is a separate object.

A *structure* of the involved input objects has to be preserved to ensure a correct behavior: the emitting part of the *sensor* is embedded in the *artifact* itself (the flashlight); the receiving part of the emitter is neither manipulated nor visible by the user; it must be within two meters of the emitting part to properly receive the localization information. From the semantic point of view, the artifact has to be manipulated as a regular flashlight.

Finally, concerning the *sensor* embedded in the flashlight, the position and orientation attributes of the flashlight are the sole liable to trigger *commands* to the application. A change in position or orientation will result in a *message* being sent.

Regarding output objects, only one is involved in the considered setting. It is a *device*, the video-projector used for the projection of the environment to explore. It supports the digital rendering of the building and allows user's *perception* of the current state of the digital application he/she is interacting with. In terms of structure, the video-projector must be placed so that the resulting projection is perceivable from the physical space in which the input objects are manipulated. Finally this device and the resulting user's perception are only affected when the *feedback* provided by the computing application is updated in terms of user's position in the cladogram.

Considering *contour* objects, several are included in the projection affecting the user's perception, such as the doors at the entrance of hallways, the windows and the texture mapped onto walls recalling the museum interiors. Another one is required to helps the user figure where its actions must be performed onto the input objects (artifact and sensor): white strips have been stuck on the floor to approximately materialize the place where the flashlight motion is within the sensing system range.

Looking at the digital domain, four *input functions* are offered to turn left/right and to move forward/backward. The input functions are directly triggered by a change of position and/or orientation transmitted by the sensor in the flashlight. These input functions serve to adjust the point of view on the representation accordingly. This adjustment naturally requires a computation through the *program modules*, which implement a finite state machine. The computing process acts with respect to the *data* representing the knowledge related to the cladogram species, expressed in XML files containing the structured set of criteria, species and related textual descriptions and illustrations.

Output functions are activated as a result of the computation and queries: concretely, they move the actual user position in the cladogram and compute the 3D representation to provide feedback related to the current criterion and species description, and update the display.

We have thus systematically used the different components of our conceptual model to describe the metaphor projection of the case study. Thanks to the links established between our model and other existing models dedicated to TUI design and analysis (see Fig. 4), it would be easily feasible to transpose this description into the concepts of one of the mentioned models. As a result, designers are able to provide a detailed view focusing on the metaphor projection and yet effectively taking advantage of knowledge, methods and properties specific to TUI.

7.4 Metaphor projection evaluation

Let us now evaluate the coherence, coverage and compliance of the metaphor. The projection of the metaphor onto the interface of this system is an instance of mapping (2) of Figs. 1 and 5: it relies on the correspondence between the metaphoric flashlight (metaphor source object) and the physical device (interface object) setting the gaze of the explorer (application object data), between the metaphorical representation of the building as a maze to explore (metaphor source object) and the cladogram (application object data) and between the manipulation of the flashlight by the explorer (interface action) and the discovery of the cladogram (application action function).

7.4.1 Coherence at component level

We analyze this projection's coherence at the component level with a reference to the TUI schema of Fig. 4 and the detailed mapping relations of Fig. 5. First, the mapping between the metaphor's objects and the interface items occurs in two cases:

- in input, the mapping depends on the user's context. The flashlight as a metaphoric object can alternatively be mapped to: (1) the interface physical device used to set the user point of view in the 3D rendering of the building representing the cladogram, as if the light beam were used to progressively disclose the virtual world; (2) the interface object representing the handle of one of the doors in the room;
- in output, the cladogram is rendered through a perceivable metaphoric representation as described in Sect. 7.2.1.

These mappings correspond to the relation (2) in Fig. 5.

Second, in our metaphor we have two types of action, explore and select, which map onto the interface actions move and point. In the application such interface actions correspond to two functions:

- a move action corresponds to executing a change in the spatial relations of the digital items;
- a point action corresponds to selecting a digital item for further processing.

Both actions refer to the relation (4) in Fig. 5.

A more detailed analysis reveals that the relations R_i between interface actions and objects on one hand and digital functions and data on the other hand hold as follows:

- moving the flashlight to right/left adjusts the viewing direction in the digital cladogram accordingly (R_1);
- moving the flashlight to the front or back depends of the activity context: (1) near one of the panels present in a room, it zooms in and out, thus enabling the user to read the content of the panel (R_2); (2) close to an open hallway, it brings the visitor inside or outside this part of the digital cladogram (R_3);
- rotating the flashlight along its main axis opens a door of the cladogram, if the physical action occurs in the appropriate area, i.e. in front of a closed door (R_4).

Hence, four relations have been identified in this metaphor. In R_1 and R_2, the flashlight maps to the digital point of view in the cladogram. In both cases the physical actions involved are mapped with digital functions. R_1 and R_2 are properly derived from the mappings existing between the metaphor's objects/digital items and actions/functions, as depicted in Fig. 5.

Regarding R_3, the flashlight still maps to the digital point of view. Actions performed in these contexts on the flashlight map to changing the position of the digital point of view. R_3 is again derived from the mappings existing between the metaphor and its implementation.

R_4 involves the flashlight which here corresponds to a door handle. Rotating the flashlight in this context rotates the door handle and thus opens the door. R_4 also derives from the correspondence between the flashlight as a metaphoric object and it's implementation in the interface as a handle.

According to our definition of coherence, the metaphor projection is thus coherent.

7.4.2 Coherence at structure level

At the structure level the coherence of the projection of the metaphor is maintained over all the relations involved in the metaphor: (1) sequences of moves of the explorer in the metaphoric building correspond to sequences of steps in the cladogram; (2) the cladogram is progressively disclosed as the explorer progressively opens the doors connecting rooms to the outgoing hallways; (3) the sequence of phylogenetic criteria which identify a species corresponds to the sequence of informative panels in the rooms along the path from the building entrance to the room denoting the species.

7.4.3 Coherence at semantic level

Finally, at the semantic level all the relations between concepts of the interface and the application domain preserve coherence: (1) the actions performed by the explorer are consistent with his/her role: look, examine, decide and proceed are applied to the initially unknown building leading to the discovery of its structure (the building topology) and contents (the information panels in the rooms); (2) the hierarchical structure of the building maps to the hierarchical structure of the cladogram in a one-to-one correspondence both in its overall topology and in the incremental discoveries made at each step; (3) the discovery proceeds stepwise by selecting, in the metaphoric world, one hallway at the time, to which corresponds one criterion at a time, according to the rules of cladistics; (4) globally, the exploration maps to the discovery of the cladogram and of the phylogenetic criteria associated to living beings.

7.4.4 Coverage

The coverage of the metaphor projection is ample, because every motion of the flashlight has a correspondence in a digital action (the simplest being changing the user point of view). Since the metaphor is a *blend*, we must evaluate also the use of the flashlight as a handle. In the proper context, it activates the only action required, which is to open a door.

The coverage is not complete, strictly speaking, because some features of the flashlight are not used, and some actions not related to orienting the flashlight beam do not correspond to digital functions: for example, pressing the flashlight switch has no effect. This action could be used, e.g., to turn on and off the light inside the environment explored, but this possibility has not been exploited.

7.4.5 Compliance

The metaphor projection is compliant because the actions taken metaphorically on the flashlight are consistent with its affordance, considering the flashlight both as a device to *enlighten* the environment (suggesting exploration) and to *highlight* a detail (pointing at it).

Its use to open doors is, however, beyond the object affordance; while it *could* be used as a handle—as it is, indeed—its shape does not suggest such a use; as noted in Sect. 7.2.2, this association has been chosen for practical reasons, to keep the interface in a unique device. Experiments with early prototypes, made with two different objects, a flashlight and a true handle, resulted in a more complex management of the interaction equipment in the museum context, and was evaluated more clumsy also from a user point of view.

8 Conclusion

Based on a review of the literature, in this paper we have first synthesized research works focusing on the understanding, description, design and evaluation of TUIs and metaphor in HCI and in reality based interfaces like TUIs. Although widely addressed in the literature, few results only are concretely supporting methodologies for the design of metaphoric interfaces. Little attention is paid to the use and evaluation of metaphors in specific and advanced forms of interaction, especially with multimodality, where different modalities may be related to different metaphors.

Focusing on the field of TUI, we have proposed a conceptual framework for evaluating the reification of metaphors in such systems based on three components. As a first component, we have identified the different mappings occurring between the metaphor source, the metaphor target, the digital application and its interface with respect to the objects, actions, data and functions involved. As a second component we have drawn a parallel between the concepts expressed in design models for TUI at one hand and the mapping between source and target domains of a metaphor at the other end. This resulted in a conceptual model which highlights the components involved in a tangible user interface and their relations to a metaphor. We have then explored and detailed three properties for a systematic evaluation of TUI metaphors reification: coherence, coverage and compliance. This conceptual framework, first illustrated on a simple metaphorical interface to an image query system, has been assessed according to its descriptive, evaluative and generative powers, and used to analyze a more complex case study in an educational context.

The conceptual framework proposed in this paper extends the current research on metaphors as it explicitly addresses their projection onto TUIs, while the models discussed in the literature are dedicated to the design of TUIs and to their specificities. This is an original approach to the analysis of metaphor for which the conceptual framework we presented in the paper provides a specific support. In addition, establishing a link between TUI models of the literature and the model included in our framework allows to keep the specificities and benefits of each approach, and supports switching from one design resource to another and to the metaphor reification evaluation.

In addition, other metaphor properties considered in the literature, such as appropriateness, consistency, suitability, affordance of interaction devices, goodness or even richness could be positioned with regards to our framework, in particular thank to the overview provided by Fig. 1 on the relations between a metaphor and an application, and refinements proposed by our framework on links 2 and 4. As a result, this work provides a supportive help for reasoning about the use, presence and design of metaphors in advanced interfaces.

As a future work, we think it is necessary to integrate metaphor evaluation with usability considerations: more specifically, there is a need to identify the contexts in which ensuring a coherent, largely covering and compliant metaphor implementation promotes the adequacy of the metaphor with the user's activity. In such a way the activity associated to usability evaluation will also be the basis for an experimental verification of the validity of our framework on a meaningful number of case studies. Finally, a definition of the relations between a tangible user interface (and, more generally, an interface) and the subsumed metaphor in a formal language would favor the automatic verification of interactive systems.

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References

1. Alty JL, Knott RP (1999) Metaphor and human–computer interaction: a model based approach. In: Nehaniv CL (ed) Computation for metaphors, analogy, and agents. Springer, Berlin, pp 307–321
2. Alty JL, Knott RP, Anderson B, Smyth M (2000) A framework for engineering metaphor at the user interface. Interact Comput 13(2):301–322
3. Andersen P (1992) Computer semiotics. Scand J Inf Syst 4:3–30
4. Anderson B, Smyth M, Knott R, Bergan M, Bergan J, Alty J (1994) Minimising conceptual baggage: making choices about metaphor. In: People and computers IX, proceedings of HCI '94. Cambridge University Press, New York, pp 179–194
5. Antle AN, Corness G, Bakker S, Droumeva M, Van Den Hoven E, Bevans A (2009) Designing to support reasoned imagination through embodied metaphor. In: Proceeding of the seventh ACM conference on creativity and cognition, CC 09, p 275
6. Averbukh V, Bakhterev M, Baydalin A, Ismagilov D, Trushenkova P (2007) Interface and visualization metaphors. In: Jacko J (ed) Human–computer interaction. Interaction platforms and techniques, lecture notes in computer science, vol 4551. Springer, Berlin, pp 13–22. doi:10.1007/978-3-540-73107-8-2
7. Averbukh V et al (2008) Searching and analysis of interface and visualization metaphors. In: Asai K (ed) Human computer interaction: new developments. InTech, New York
8. Bakker S, Antle A, Van Den Hoven E (2012) Embodied metaphors in tangible interaction design. Personal Ubiquitous Comput 16(4):433–449
9. Barr P (2003) User-interface metaphor in theory and practice. Master's thesis, Victoria University of Wellington, Department of Mathematical and Computing Sciences
10. Barr P, Biddle R, Noble J (2002) A taxonomy of user interface metaphors. In: Proc. of SIGCHI-NZ Symposium On Computer-Human Interaction
11. Barr P, Biddle R, Noble J (2003) A semiotic model of user-interface metaphor. In: 6th International Workshop on Organisational Semiotics
12. Beaudouin-Lafon M (2000) Instrumental interaction. In: Proceedings of the SIGCHI conference on human factors in computing systems—CHI '00, pp 446–453
13. Beaudouin-Lafon M (2004) Designing interaction, not interfaces. In: Proceedings of the working conference on advanced visual interfaces. ACM, New York, AVI '04, pp 15–22
14. Black M (1954) Metaphor. Proc Aristot Soc N Ser 55:273–294

15. Blackwell AF (2006) The reification of metaphor as a design tool. ACM Trans Comput Hum Interact 13(4):490–530
16. Bortolaso C, Dubois E, Duranthon F, Bach C (2011) Co-design of interactive museographic exhibits: the MIME case study. In: Ciolfi L, Scott K, Barbieri S (eds) Re-thinking technology in museums. University of Limerick, Limerick, pp 37–48
17. Carroll JM, Mack RL (1985) Metaphor, computing systems, and active learning. Int J Man Mach Stud 22(1):39–57
18. Celentano A, Dubois E (2012) Metaphor modelling for tangible interfaces evaluation. In: Proceedings of the international working conference on advanced visual interfaces. ACM, New York, AVI '12, pp 78–81
19. Coutaz J, Nigay L, Salber D, Blandford A, May J, Young R (1995) Four easy pieces for assessing the usability of multimodal interaction: the CARE properties. In: Nordby K, Helmersen PH, Gilmore DJ, Arnesen SA (eds) Proceedings of INTERACT '95, IFIP TC13 interantional conference on human–computer interaction. Chapman & Hall, Lillehammer, pp 115–120
20. Coutrix C, Nigay L (2006) Mixed reality: a model of mixed interaction. In: Proceedings of the working conference on Advanced visual interfaces, AVI2006. ACM Press, New York, pp 43–50
21. Dubois E, Gray P (2007) A design-oriented information-flow refinement of the ASUR interaction model. In: Gulliksen J, Harning M, Palanque P, van der Veer G, Wesson J (eds) Proceedings of the international conference on engineering interactive systems EIS'07, vol 4940. Springer, Berlin, pp 465–482
22. Dubois E, Bortolaso C, Bach C, Duranthon F, Blanquer-Maumont A (2011) Design and evaluation of mixed interactive museographic exhibits. Int J Arts Technol 4(4):408–441
23. Fishkin K (2004) A taxonomy for and analysis of tangible interfaces. Pers Ubiquit Comput 8(5):347–358
24. Forceville CJ, Urios-Aparisi E (2009) Chapter 1. Introduction. In: Forceville CJ, Urios-Aparisi E (eds) Multimodal metaphor. Mouton de Gruyter, Berlin, pp 3–17
25. Gero J (2004) The situated function–behaviour–structure framework. Des Stud 25(4):373–391
26. Hartshorne C, Weiss P (eds) (1936) Collected papers of Charles Sanders Peirce, vol 1–6. Harvard University Press, Cambridge
27. Hennig W (1950) Grundzüge einer Theorie der Phylogenetischen Systematik. Deutscher Zentralverlag, Berlin
28. Hochmair H, Luttich K (2006) An analysis of the navigation metaphor-and why it works for the world wide web. Spatial Cognit Comput 6(3):235–278
29. Hornbaek K, Frokjaer E (2002) Evaluating user interfaces with metaphors of human thinking. In: Carbonell N, Stephanidis C (eds) Proceedings of the User interfaces for all 7th international conference on Universal access: theoretical perspectives, practice, and experience (ERCIM '02). Springer, Berlin, pp 486–507
30. Hornecker E (2012) Beyond affordance. In: Proceedings of the sixth international conference on tangible, embedded and embodied interaction, TEI '12, New York, New York, USA. ACM Press, New York, p 175
31. Hornecker E, Buur J (z2006) Getting a grip on tangible interaction: a framework on physical space and social interaction. In: Proc. CHI 2006. ACM Press, New York, pp 436–446
32. Hurtienne J (2009) Image schemas and design for intuitive use. Exploring new guidance for user interface design. PhD thesis, Technische Universitat Berlin
33. Hurtienne J, Blessing L (2007) Design for intuitive use—testing image schema theory for user interface design. In: ICED '07, 16th international conference on engineering design, Paris, France, pp 1–12
34. Hurtienne J, Israel JH (2007) Image schemas and their metaphorical extensions: intuitive patterns for tangible interaction. In: Proceedings of the 1st international conference on Tangible and embedded interaction. ACM Press, New York, pp 127–134
35. Hurtienne J, Stößel C, Sturm C, Maus A, Rötting M, Langdon P, Clarkson J (2010) Physical gestures for abstract concepts: inclusive design with primary metaphors. Interact Comput 22(6):475–484
36. Indurkhya B (1986) Constrained semantic transference: a formal theory of metaphors. Synthese 68(3):515–551
37. Ishii H (2008) Tangible bits: beyond pixels. In: Proceedings of the 2nd international conference on Tangible and embedded interaction. ACM, New York, TEI '08, pp xv–xxv
38. Ishii H (2008) The tangible user interface and its evolution. Commun ACM 51(6):32–36
39. Ishii H, Ben-Joseph E, Underkoffler J, Yeung L, Chak D, Kanji Z, Piper B (2002) Augmented urban planning workbench: overlaying drawings, physical models and digital simulation. In: ISMAR '02, proceedings of the 1st international symposium on mixed and augmented reality. IEEE Computer Society, Washington, DC, pp 203–211
40. Jacob RJK, Girouard A, Hirshfield LM, Horn MS, Shaer O, Solovey ET, Zigelbaum J (2008) Reality-based interaction. In: Proceeding of the twenty sixth annual CHI conference on human factors in computing systems, CHI 08. ACM Press, New York, p 201
41. Johnson M (1987) The body in the mind. University of Chicago Press, Chicago
42. Jordà S, Geiger G, Alonso M, Kaltenbrunner M (2007) The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In: Proceedings of the 1st international conference on tangible and embedded interaction. ACM, New York, pp 139–146
43. Jourde F, Laurillau Y, Morán AL, Nigay L (2008) Towards specifying multimodal collaborative user interfaces: a comparison of collaboration notations. In: Interactive systems. Design, specification, and verification, 15th international workshop, DSV-IS, Kingston, Canada, pp 281–286
44. Kay AC (1972) A personal computer for children of all ages. In: Proceedings of the ACM annual conference, vol 1. ACM, New York
45. Kintsch W (2000) Metaphor comprehension: a computational theory. Psychonom Bull Rev 7(2):257–266
46. Koleva B, Benford S, Ng KH, Rodden T (2003) A framework for tangible user interfaces. In: In workshop proceedings on real world user interfaces, mobile HCI conference 03, pp 257–264
47. Lakoff G (1987) Women, fire, and dangerous things: what categories reveal about the mind. University of Chicago Press, Chicago
48. Lakoff G (1993) The contemporary theory of metaphor. Metaphor and thought, pp 202–251
49. Lakoff G, Johnson M (1980) Metaphors we live by. University of Chicago Press, Chicago
50. Lamata P, Ali W, Cano A, Cornella J, Declerck J, Elle OJ, Freudenthal A, Furtado H, Kalkofen D, Naerum E, Samset E, Sánchez-Gonzalez P, Sánchez-Margallo FM, Schmalstieg D, Sette M, Stüdeli T, Sloten JV, Gómez EJ (2010) Augmented reality for minimally invasive surgery: overview and some recent advances. In: Maad S (ed) Augmented reality. InTech, Croatia
51. Macaranas A, Antle AN, Riecke BE (2012) Bridging the gap. In: Proceedings of the sixth international conference on tangible, embedded and embodied interaction, TEI '12. ACM, New York, p 161
52. Mackay WE, Fayard AL, Frobert L, Médini L (1998) Reinventing the familiar: exploring an augmented reality design space for air traffic control. In: Proceedings of the SIGCHI conference on human factors in computing systems. ACM Press/Addison-Wesley Publishing Co., New York, CHI '98, pp 558–565
53. Maquil V, Ras E, Zephir O (2011) Understanding the characteristics of metaphors in tangible user interfaces. Mensch Comput 2011:1–6
54. Maquil V, Zephir O, Ras E (2012) Creating metaphors for tangible user interfaces in collaborative urban planning: questions for designers and developers. In: Dugdale J, Masclet C, Grasso MA,

Boujut JF, Hassanaly P (eds) From research to practice in the design of cooperative systems: results and open challenges. Springer, London, pp 137–151
55. Marcus A (1994) Managing metaphors for advanced user interfaces. In: Proceedings of the workshop on advanced visual interfaces. ACM, New York, AVI '94, pp 12–18. http://doi.acm.org/10.1145/192309.192317
56. McGee D, Cohen PR (2001) Creating tangible interfaces by augmenting physical objects with multimodal language. In: Proceedings of the 6th international conference on Intelligent user interfaces. ACM, New York, IUI '01, pp 113–119
57. McNerney TS (2004) From turtles to tangible programming bricks: explorations in physical language design. Pers Ubiquitous Comput 8(5):326–337. doi:10.1007/s00779-004-0295-6
58. Norman DA (2002) The design of everyday things. Basic Books, New York
59. Oppl S, Stary C (2011) Towards informed metaphor selection for TUIs. In: Proceedings of the 3rd ACM SIGCHI symposium on engineering interactive computing systems, EICS '11. ACM, New York, pp 247–252
60. Perlman R (1976) Using computer technology to provide a creative learning environment for preschool children. Tech. rep., MIT AI Lab memo 360, Logo memo 24
61. Pittarello F, Stecca R (2010) Querying and navigating a database of images with the magical objects of the wizard Zurlino. In: IDC 2010, 9th international conference on interaction design and children. ACM Press, New York, pp 250–253
62. Pittarello F, Stecca R (2011) Mapping physical objects to digital functions: a tangible interface for querying and navigating a multimedia database. In: DEXA '11, proceedings of the 22nd international workshop on database and expert systems applications. IEEE Computer Society, New York, pp 134–138
63. Poynor R (1995) The hand that rocks the cradle. ID the international design magazine, pp 60–65
64. Praggeljaz Group (2007) MIP: a method for identifying metaphorically used words in discourse. Metaphor Symbol 22(1):1–39
65. Price S, Jewitt C (2013) A multimodal approach to examining 'embodiment' in tangible learning environments. In: Proceedings of the 7th international conference on tangible, embedded and embodied interaction. ACM, New York, TEI '13, pp 43–50
66. Sajaniemi J, Stützle T (2007) Lightweight techniques for structural evaluation of animated metaphors. Interact Comput 19(4):457–471
67. Shaer O, Hornecker E (2010) Tangible user interfaces: past, present, and future directions. Found Trends Hum Comput Interact 3(1–2):1–137
68. Sickenius de Souza C (1993) The semiotic engineering of user interface languages. Int J Man Mach Stud 39(5):753–773
69. Steinhart E (2005) Generating & interpreting metaphors with NETMET. APA Newslett 4(2):3–7
70. Suzuki H, Kato H (1995) Interaction-level support for collaborative learning: algoblock—an open programming language. In: The first international conference on computer support for collaborative learning. L. Erlbaum Associates Inc., Hillsdale, CSCL '95, pp 349–355. doi:10.3115/222020.222828
71. Svanaes D, Verplank W (2000) In search of metaphors for tangible user intefaces. In: Proceedings of DARE 2000 on designing augmented reality environments (DARE '00), pp 121–129
72. Ullmer B, Ishii H (2000) Emerging frameworks for tangible user interfaces. IBM Syst J 39(3–4):915–931
73. Ullmer B, Ishii H, Jacob R (2005) Token+constraint systems for tangible interaction with digital information. ACM Trans Comput Hum Interact 12(1):81–118
74. Underkoffler J, Ishii H (1999) URP: a luminous-tangible workbench for urban planning and design. In: Proceedings of the SIGCHI conference on Human factors in computing systems, CHI '99. ACM Press, New York, pp 386–393
75. Vaananen K, Schmidt J (1994) User interfaces for hypermedia: how to find good metaphors? In: Conference companion on Human factors in computing systems (CHI '94), pp 263–264
76. Van Hees K, Engelen J (2013) Equivalent representations of multimodal user interfaces. Univers Access Inf Soc 12(4):339–368
77. Wagensberg J (2005) The "total" museum, a tool for social change. História, Ciências, Saúde Manguinhos 12(supplement):309–321
78. Zhou CL, Yang Y, Huang XX (2007) Computational mechanisms for metaphor in languages: a survey. J Comput Sci Technol 22(2):308–319